Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Innovations in Agriculture and Food Supply in Response to the COVID-19 Pandemic

In human history, the long-term expansion of populations has been limited by the availability of food and constraints of disease (Diamond, 1997). The domestication of plants and animals has facilitated the development of human societies, and the resulting larger human populations have increased the risk of major disease outbreaks (pandemics). The recent COVID-19 pandemic resulted from the emergence of a disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). This has caused major disruption to economic activity with severe restrictions on international travel. The impact on agriculture and global food security will be complex (Torero, 2020), and many of the consequences are yet to be identified and understood (Jámbor et al., 2020). Despite growing stocks of foods such as cereals (FAO, 2020), it has been estimated that the number of people facing a food crisis will grow from 135 million to 265 million by the end of 2020 (Anthem, 2020; Figure 1). The pandemic has added to the food security challenges posed by climate change and major conflicts, both of which have been major factors contributing to recent food insecurity. Plant scientists need to determine how investment in innovation needs to change in response to the pandemic. Concerns about shortages of labor and food safety will intensify efforts to use automation at all stages in the food production system to ensure supply. The response to transport and trade disruption may prompt accelerated efforts to develop protected cropping to support food production much closer to the point of consumption. Both of these trends will add to the demand for new crop varieties that satisfy the growing demands of consumers and drive additional research efforts, including accelerated application of emerging plant breeding technologies (Henry, 2019a) for production in these rapidly evolving agricultural environments.

Impact on Food Demand

The management of the current pandemic to date suggests little impact on global food demand due to human population loss. The impacts on the food security of people in the developed world have been relatively minor so far, but more serious problems are emerging in developing countries (Somner et al., 2020). In developed countries, demand for some stable foods, such as rice, was initially very high with consumers purchasing large supplies as a response to fears of food shortages. Some food consumption patterns have changed due to people being restricted to eating at home rather than in restaurants (Torero, 2020). In many developing countries, COVID-19 had a severe impact on employment and incomes, creating a major food crisis for growing numbers of people unable to afford food. Demand for emergency food supplies is likely to grow.

Impact on Food Supply

Disruption of food supply is a major challenge resulting from COVID-19. Labor for harvesting, processing, transport, and distribution has been threatened by restriction on movement and management of risks of the spread of the virus. The closing of national borders has limited the availability of migrant workers. Food processing facilities have been closed due to infection of workers with the virus. Longer-term impacts of the pandemic are possible if agricultural and food supply chains are managed more conservatively to retain high stock levels as a buffer against future pandemics. International air transportation (International Transport forum, 2020) has been severely disrupted by COVID-19 and the movement of some high-value food shipped by air has been more difficult. The long-term policy implications of the pandemic for global food trade remain unclear. The pandemic has focused attention on the critical importance of continued food production and distribution, and some of the approaches developed to ensure food supply might be retained in the longer term.

Impact on Agricultural Research

The COVID-19 pandemic has been disruptive for agricultural and food research. Many research labs have closed and many global research conferences have been canceled. reducing direct contact between researchers. Researchers have responded by working online as much as possible and adjusting laboratory working environments to have lower numbers of researchers per unit area of laboratory space. Increased shift work has allowed researchers to work at different times of the day and continue to have laboratory access. One short-term impact has been the diversion of researchers to COVID-19 research projects (Capell et al., 2020). Agricultural researchers with appropriate skills have been tasked with supporting research such as developing vaccines, assessing anti-viral treatments, improving or deploying diagnostic tests, and supporting contact tracing of people infected with the virus. The pandemic will result in some resetting of research priorities to focus on making agriculture and food production more resilient to such events. The long-term impact of COVID-19 on the progress of agricultural and food research remains unclear.

Long-Term Impact

The large global economic impact of COVID-19 may have implications for agriculture and food production (Somner et al., 2020). The global economy has been severely affected by curtailment of economic activity by people isolating to minimize spread of the virus.

Some of the long-term impacts of COVID-19 may be driven by fear of future pandemics. This will result in risk management

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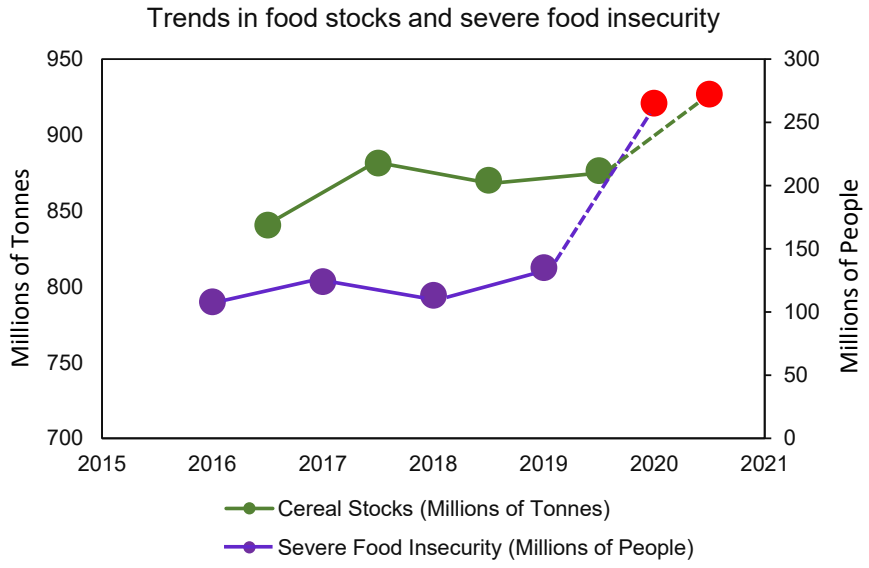

Figure 1. Food Insecurity Increases Despite Growing Food Stocks.
Predicted changes in world cereal stocks (FAO, 2020) and numbers of people who are acutely food insecure in crisis or worse (IPC/CH phase 3 or above). Population numbers based upon Global report on food crisis, 2020 from the World Food Program. Numbers at the end of 2020 (Anthem, 2020) estimated due to the impact of COVID-19.

strategies that could have an impact on agriculture and food production. People and countries could aim to be more self-sufficient in food production to reduce reliance on food supply from other places or countries. Trends that may emerge could include more attempts at self-sufficiency by consumers growing their own food at home, and more home cooking because of experiences during the pandemic. More significant will be the approach of governments to food security with possible impacts on global trade in foods. Export of foods maybe blocked and imports restricted to force local production as strategies to protect the food supply in future pandemics.

The adverse impact of COVID-19 on the global economy may also result in a renewed risk of accelerated population growth that could add significantly to food insecurity. While economic difficulties result in lower population growth rates in developed countries (Sobotka et al., 2011), poverty is a major factor contributing to rapid population growth in developing countries (Van Bavel, 2013). If COVID-19 prevents escape from poverty in these countries, population growth may be higher than previously predicted and put more pressure on food security.

Changes and Trends to Meet the Demand

Many responses to the pandemic have resulted in changes in agriculture and food production that may persist in the longer term. In some situations, more emphasis may be placed on automation of food production and processing to avoid the risks of using labor that may be unavailable due to illness or due to the restriction on labor migration. This could result in more investment in automation of harvesting and processing, minimizing manual steps in the whole production chain. The automation of food production in these systems could also eliminate the risks of contamination of the food during production. COVID-19 contamination of foods has not been a problem, but other organisms in future pandemics might pose this risk.

The experience of trade disruptions during the pandemic may add to the trend toward more protected cropping induced by climate change (Henry, 2019b). All forms of protected cropping, including advanced vertical farming, may be more capital intensive but have the potential to reduce the risks associated with food production. Protected cropping allows production close to the point of consumption regardless of the environment required for the growth of the crop and eliminates the problems of long-distance transportation, which may be limited in a pandemic. These innovations may also bring the advantages of automation described above.

Accelerated deployment of improved crop varieties using emerging genetic technologies could contribute significantly to the delivery of the productivity gains required to ensure food security. The pandemic has added extra urgency to this work, which has recently been driven by the need to respond to climate change. Gene editing technologies have a chance of being more widely accepted and understood than earlier genetically modified approaches and have the potential for very rapid advances in food production if combined with protected cropping. The use of controlled environments for food production allows genetics to focus on enhancing the nutritional value and consumer attractiveness of the food products. The approach to food product innovation is likely to be one involving iterative cycles of designing and building the target genotype (using plant biotechnology equipped with advanced genomics and gene editing) and production environment (engineering optimal environments that can be created cost effectively) for sustainable and reliable production regardless of climate change or pandemics (Pouvreau et al., 2018). The need to respond to the pandemic might contribute to wider public acceptance of the use of science and technology to support food security. These advanced strategies will need to be complemented by continued efforts to support traditional subsistence farmers with appropriate extension, policies, and technologies for their needs. However, some of these interventions will also be based on similar technology inputs (e.g., climate-resilient crops for small-holder environments).

Increased investment in agricultural research and development would support enhanced food security. Advanced technologies need to be adopted globally in each region to deliver local food production capability that can provide secure sources of food in future pandemics. This will require public and private policies that support regional investment in food production infrastructure and acceptance of new technologies. Plant sciences have a major role to play (Weng, 2020) in not only addressing the

needs of a post-COVID world but also the long-term challenges of climate change, population growth, environmental degradation, and food security.

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